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Recent Developments in Spray Cooling of Deep Mines

By Edward D. Thimons, John F. McCoy, and John R. Marks

UNITED STATES DEPARTMENT OF THE INTERIOR

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Report of Investigations 9000

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UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Btu/(lb·°F)	British thermal unit per pound per degree Fahrenheit	kW	kilowatt
		lb/gal	pound per gallon
°C	degree Celsius	m	meter
cfm	cubic foot per minute	mg/L	milligram per liter
°F	degree Fahrenheit	mm	millimeter
ft	feet	m^3/s	cubic meter per second
gal/min	gallon per minute	MW	megawatt
hp	horsepower	Pa	pascal
in	inch	pct	percent
kg/s	kilogram per second	psi	pound per square inch
kJ/(kg·°C)	kilojoule per kilogram per degree Celsius	st	short ton
kPa	kilopascal		

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RECENT DEVELOPMENTS IN SPRAY COOLING OF DEEP MINES

By Edward D. Thimons,[1] John F. McCoy,[2] and John R. Mark[3]

ABSTRACT

This report describes in detail four water spray coolers designed for cooling deep underground mines and discusses the performance of three of them in deep-mine field tests. The four spray coolers were designed and built as part of a Bureau of Mines program to investigate direct-contact (warm air to cool water) spray cooling systems.

A single-stage cooling unit was tested in a New Mexico uranium mine, and a two-stage cooler and a three-stage cooler were tested in a South Dakota gold mine. To date, all three coolers have performed well under in-mine conditions and have required only minimal maintenance. Tests on a fourth cooler, a three-stage unit, are underway, but have not been completed.

INTRODUCTION

The need for more efficient mine refrigeration equipment is greater than ever, as increasing numbers of U.S. mines are being operated at greater depths in order to reach minable ore deposits. The combination of high temperatures and high humidities encountered at these depths makes a comfortable working environment difficult and expensive to maintain. Many ore bodies mined today could not be mined without cooling of the underground environment. Miners' safety, comfort, and productivity all suffer if air refrigeration needs are not satisfied.

In deep, hot mines where virgin rock temperatures can exceed 130° F (54° C), mine cooling has conventionally been accomplished through the use of finned-coil coolers. These conventional coolers are similar in construction to automotive radiators. In these coolers, chilled mine water passes through the finned coils and cools the warm mine air as the air is blown past the coils. In water spray coolers, heat exchange is accomplished by direct contact between the warm mine air and cold water sprays. The water spray coolers described in this report are efficient and economical devices for dealing with the heat problem encountered in deep mines.

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FACTOR-OF-MERIT ASSESSMENT OF COOLER PERFORMANCE

Coolers are commonly regarded as having a specified cooling capacity of so many kilowatts; however, this can be misleading, since the cooling capacity of a unit depends not only on rated power but also on the inlet fluid temperatures and flow rates. As an illustration, consider the extreme case of a cooler supplied with water at the same temperature as the input airstream temperature. Obviously, the cooling capacity under these conditions is nil. A better way is needed to characterize cooling performance.

In the research described in this report, the performance of the cooling units was characterized by the factor-of-merit, or F-factor, originally developed by Whillier (3)[4] and improved by Bluhm (1). The F-factor of a cooler is independent of operating temperature and barometric pressure. It is equivalent to the overall heat transfer coefficient for a conventional heat exchanger. The F-factor may also be thought of as the cooler efficiency when the capacity factor, R (as defined below), is one.

The following nomenclature is relevant to F-factor calculations:

C = thermal capacity of liquid water [1.0 Btu/(lb·°F), or 4.18 kJ/(kg·°C)].

C' = average equivalent thermal capacity of humid air between t_{a1} and t_{w1}, Btu/(lb·°F) or kJ/(kg·°C).

E_w = effectiveness of cooling water or water efficiency.

F = factor-of-merit or F-factor.

G = mass flow of air to the cooler, gal/min (kg/s).

L = mass flow of cooling water to the cooler, gal/min (kg/s).

$N = \frac{F}{1-F} \Big/ R^{0.4}$.

P = cooling power or cooling duty of the cooler (refrigeration), kW.

R = capacity factor (LC/GC').

t_{a1} = air wet-bulb temperature into the cooler, °F (°C).

t_{ao} = air wet-bulb temperature out of the cooler, °F (°C).

t_{w1} = temperature of cooling water into the cooler, °F (°C).

t_{wo} = temperature of cooling water out of the cooler, °F (°C).

If the water efficiency is measured at some known arbitrary capacity factors, the following semi-empirical relationship permits calculation of the F-factor:

$$E_w = \frac{1-e^{-N(1-R)}}{1-Re^{-N(1-R)}}, \quad R \neq 1$$

$$E_w = F \text{ when } R = 1$$

where $N = \frac{F}{1-F} \Big/ R^{0.4}$.

Once the F-factor is determined in this manner, water efficiencies under other conditions may be predicted. The F-factor may also be used to determine when cooler maintenance is required. If the F-factor, input flow, and temperature conditions of a cooler are known, the cooling power may be calculated as follows:

$$P = E_w LC(t_{a1}-t_{w1}),$$

where E_w is obtained from the first equation above.

[4]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

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DESCRIPTIONS OF LARGE-SCALE SPRAY COOLERS

SINGLE-STAGE COOLER

The original spray cooler (fig. 1) was a single-stage unit (i.e., it had only one spray manifold). In this unit, an inlet transition and diffuser plate aids in spreading the inlet air jet to achieve more uniform flow. The air then passes through plates constructed of corrugated fiberglass roofing material and stacked as shown in figure 2 to produce channels. Air leaving these channels passes through the cooling water spray pattern shown in figure 1. Mist is removed from the cooling air in a wave-plate eliminator before it exits through the transition section.

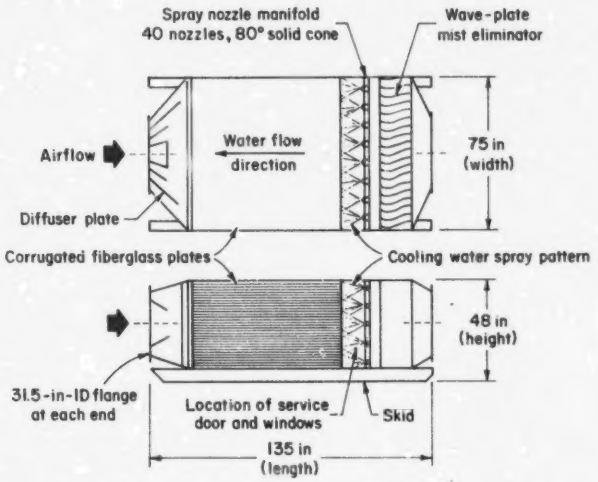

FIGURE 1. - Schematic of single-stage cooler, overhead (top) and side (bottom) views.

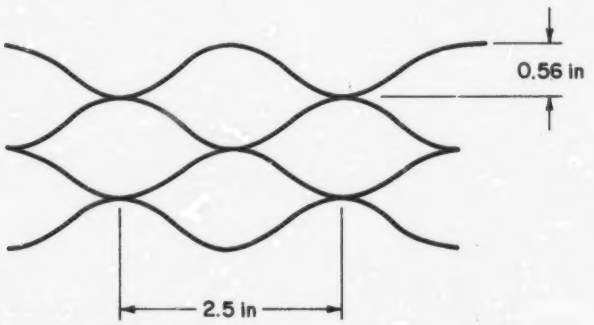

FIGURE 2. - Configuration of stacked corrugated fiberglass in single-stage cooler.

Cooling water is sprayed from a manifold at a rate of 100 gal/min (6.31 kg/s), at 30 psi (208 kPa), through 40 spray nozzles. Each nozzle produces an 80°-angle solid-cone spray. The spray pattern produces a uniform water flux across the downwind end of the corrugated fiberglass. Water entering the channels runs along the bottom of the channels, draining out of the upwind end of the cooler. (The cooler is installed so that it is pitched slightly downward at the upwind end.) The water spray direction and channel flow direction are opposite to the airflow direction, and the result is a counterflow cooling effect. Water is drained from the low end of the cooler onto the floor.

TWO-STAGE COOLER

A previously developed bulk cooler concept was adapted into a two-stage design (fig. 3) with an overall length of (151.5 in) (3,848 mm). The downwind transition section of this two-stage cooler can be

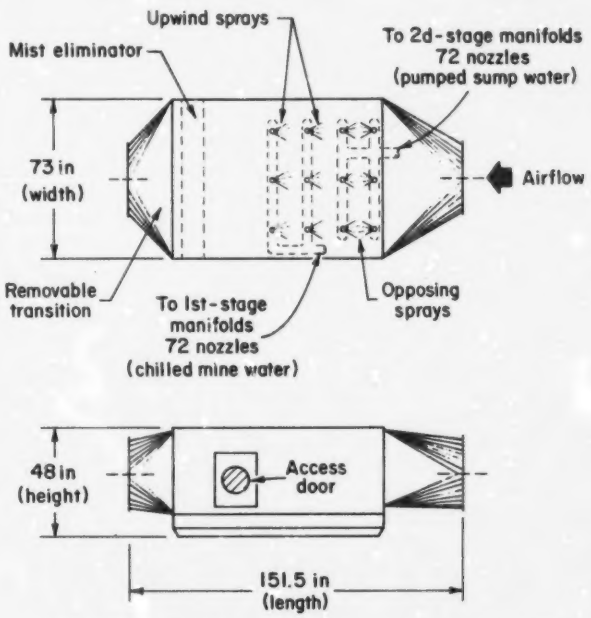

FIGURE 3. - Schematic of two-stage cooler, overhead (top) and side (bottom) views.

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removed to facilitate in-mine transportation. Increased cooler length permits the use of a somewhat longer inlet transition, yet in this study, diffuser plates were not needed to achieve uniform flow.

Hot air entering the cooler encounters the second water stage first, producing a desirable counter-flow effect. The second water stage consists of a pair of spray nozzle manifolds holding 36 nozzles each. These manifolds spray in direct opposition to each other, as shown in figure 3. The design flow rate for the 72 nozzles is 100 gal/min (6.31 kg/s) at 20 psi (138 kPa). Each spray nozzle produces a 72°-angle hollow-cone spray. Water is supplied to the second stage by a remotely located 3-hp (2.2-kW) pump, which draws water from the sump of the first water stage.

Air leaving the second water stage passes through the spray pattern of the first water stage. The first water stage is similar to the second except that all 72 sprays are directed against the airflow. Cold service water is supplied to the first stage at 100 gal/min (6.31 kg/s) and at 20 psi (138 kPa).

The air is demisted by a wave-plate eliminator before exiting the cooler. The water removed from the exiting airstream drains to a sump that collects water from the first stage (and this water is supplied to the second water stage as described previously). Water from the second water stage falls to a second water stage sump, where it drains out onto the floor.

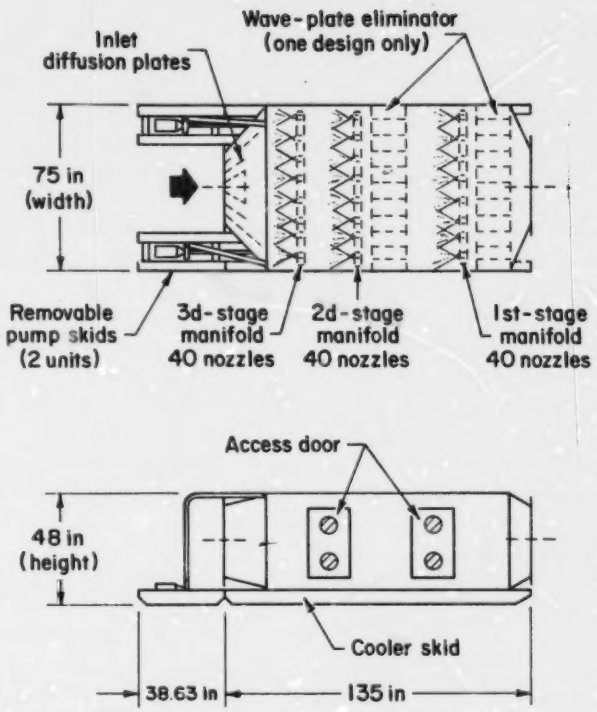

FIGURE 4. - Schematic of three-stage cooler, overhead (top) and side (bottom) views.

THREE-STAGE COOLER

Both three-stage cooler designs can be understood by reference to figure 4. These units incorporate dual 7.5-hp (5.6-kW) pumps on skids that are separable from the main cooler skids. The air-inlet transition is identical in design to that used on the single-stage cooler, and all three water spray manifolds are identical. A uniform array of forty 80°-angle full-cone spray nozzles is installed on each manifold. The 40 nozzles delivered 100 gal/min (6.31 kg/s) at 30 psi (207 kPa).

In operation, hot air passes successively through the third and second water stages. In one design, a wave-plate mist eliminator demists the air before it passes through the first water stage. The other design does not have this demisting stage. The intent was to evaluate any effect the mist eliminator might have on thermal performance. Initial results indicated there is a positive effect. Downwind of the first water stage, the air is demisted and exits the cooler.

MINE APPLICATION OF COOLERS

MOUNT TAYLOR MINE

The single-stage cooler was installed in the Mount Taylor Mine in San Mateo, NM, in June 1982. The mine was a developing uranium mine that was experiencing severe heat and humidity problems. It had a virgin rock temperature of 127° F

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(53° C) on the 3,200 level and was producing about 5,000 gal/min (189.3 kg/s) of water at approximately 120° F (49° C). The cooler was located on the 3,200 level in a drift where the dry-bulb air temperature was 105° F (40.5° C). It was hung from the roof by chains to keep it out of the way of moving equipment and was pitched with the air-inlet (water-outlet) end 6 in (152.4 mm) lower than the air-outlet end for proper water drainage through the channels in the corrugated fiberglass (fig. 5). Mine engineers were pleased with the cooler, which remained in constant operation without any maintenance for 4 months until the mine was closed due to falling uranium prices.

HOMESTAKE GOLD MINE

The Homestake Gold Mine, located in the Black Hills of South Dakota, has been operating since 1876. Operations currently extend to the 8,000 level, where the virgin rock temperature is 133° F (56° C).

Air-conditioning was first used in 1963. At that time, spot coolers with reciprocating compressors delivered cooled air to development headings. In 1979, a plant with 580 refrigeration tons (2.1 MW) of cooling power was installed to chill service water for the deepest work areas. About 55 pct of the 950-gal/min (60-kg/s) flow rate was used in cooling coils at stope entrances, but air and water side fouling significantly reduced airflow and heat transfer. Homestake subsequently entered into a cooperative agreement with the Bureau of Mines and Foster-Miller, Inc., to evaluate small direct-contact spray coolers (2). When connected to a 15-hp (11-kW) fan and ventilation bag, a single spray cooler will deliver 5,000 cfm (2.36 m^3/s) and 14 refrigeration tons (50 kW) of cooling power to a work area. The evaluation was very successful. Homestake currently uses 46 small spray coolers.

A steady transition at the Homestake Mine from cut-and-fill techniques to

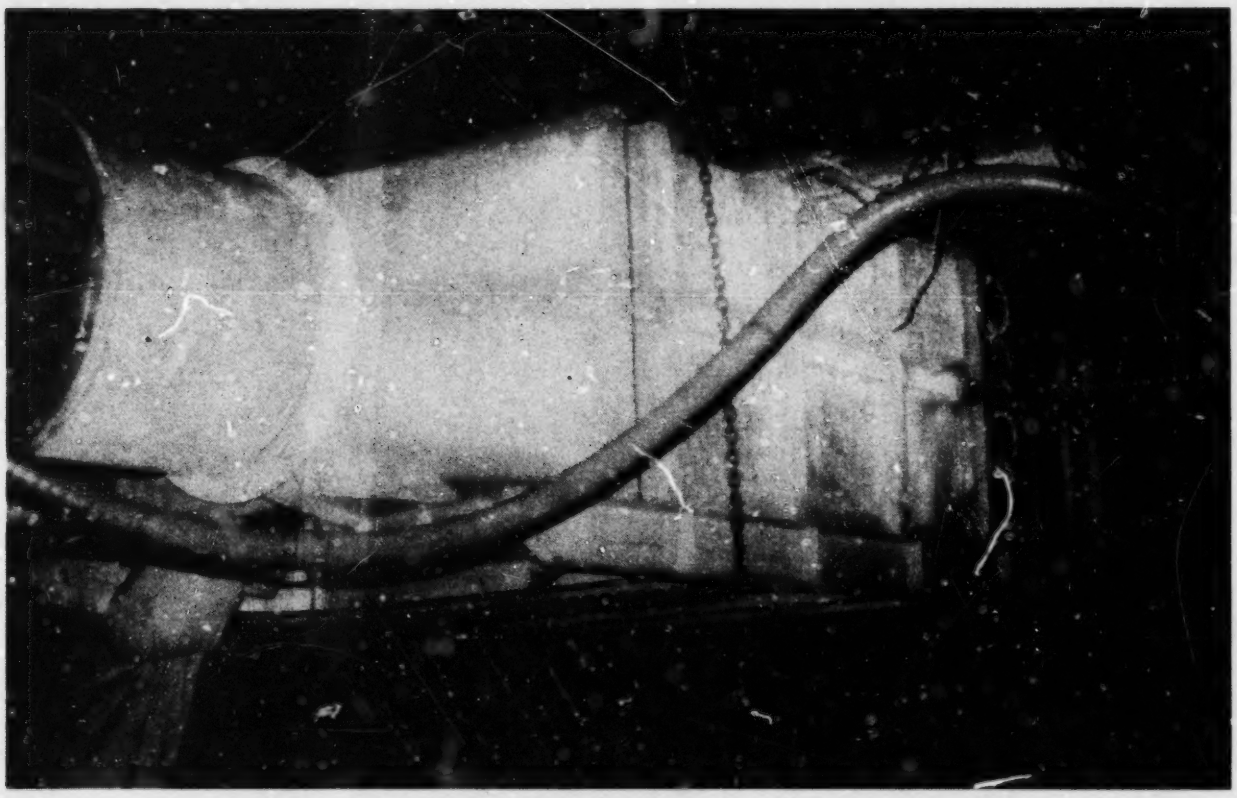

FIGURE 5. - Single-stage cooler installed in Mount Taylor Mine.

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bulk-mining methods, with increasing dependence on diesel LHD's, prompted the mine to search for a more compatible ventilation method. Late in 1982, the Bureau offered Homestake a chance to test three large spray coolers.

The coolers were originally designed for duct and bag, but were installed as limited-area bulk coolers at Homestake. Both limited-area and primary bulk coolers use airways to transport refrigeration to work areas. This obviates the need for large numbers of small fans, cooling devices, and ducting. Unlike primary bulk cooling, however, limited-area bulk cooling achieves higher positional efficiency and percent utilization. Work areas are assured a constant through-flow of cooled air.

The first three-stage cooler with an interstage mist eliminator, was installed on the 7,100 level in March 1983 (fig. 6). It services a three-panel vertical crater retreat (VCR) drawpoint area, a charging chamber on the level above, and a development heading. Supplemental cooling is required on the level above due to the magnitude of the heat load. The cooler gained immediate miner and supervisor acceptance, and has been operating continuously since installation.

The two-stage cooler was installed on the 7,400 level in February 1984 (fig. 7). It ventilates a large mechanized cut-and-fill stope-and-ramp system. Again, the large heat load necessitates supplemental cooling. The higher air flow rate effectively disperses diesel emissions and provides a uniform temperature profile within the large stope.

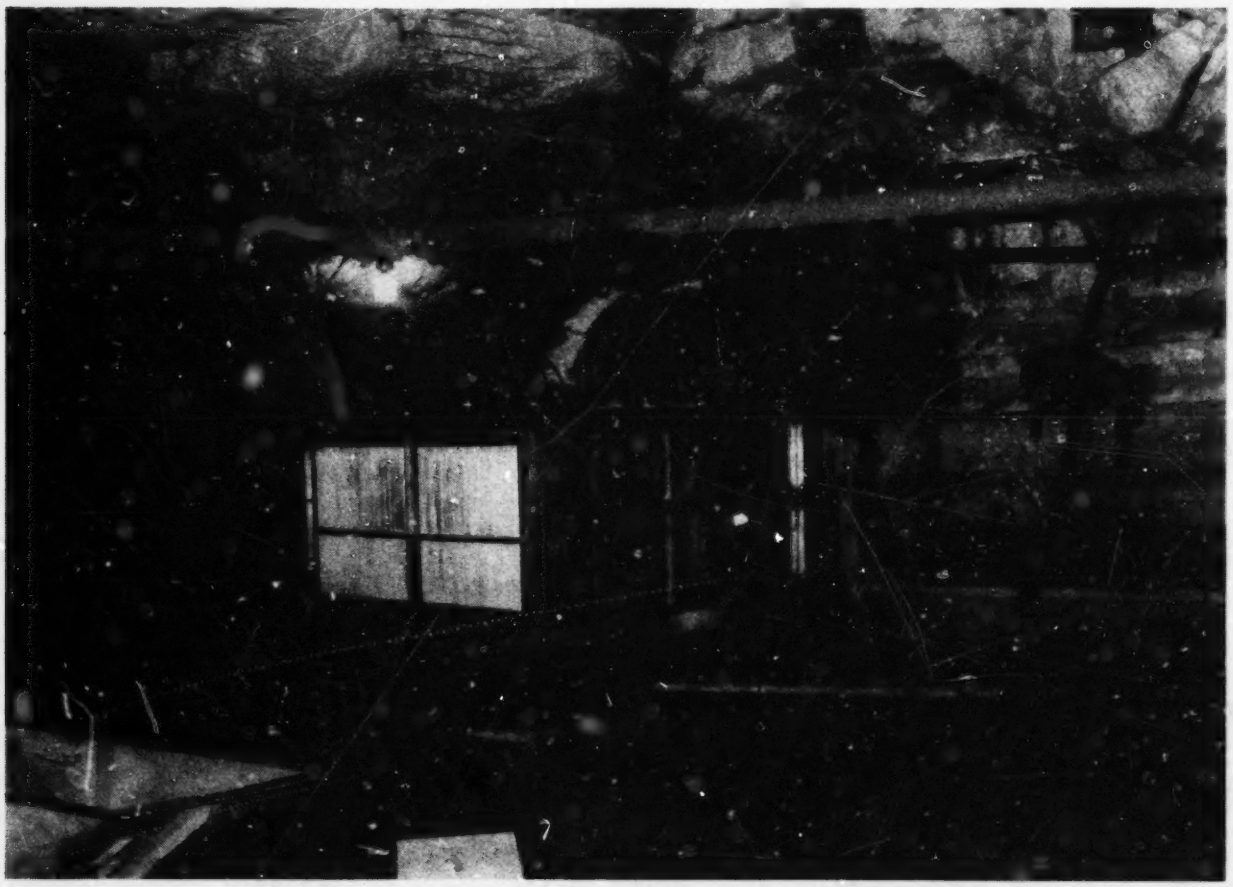

FIGURE 6. - Three-stage cooler installed in Homestake Gold Mine.

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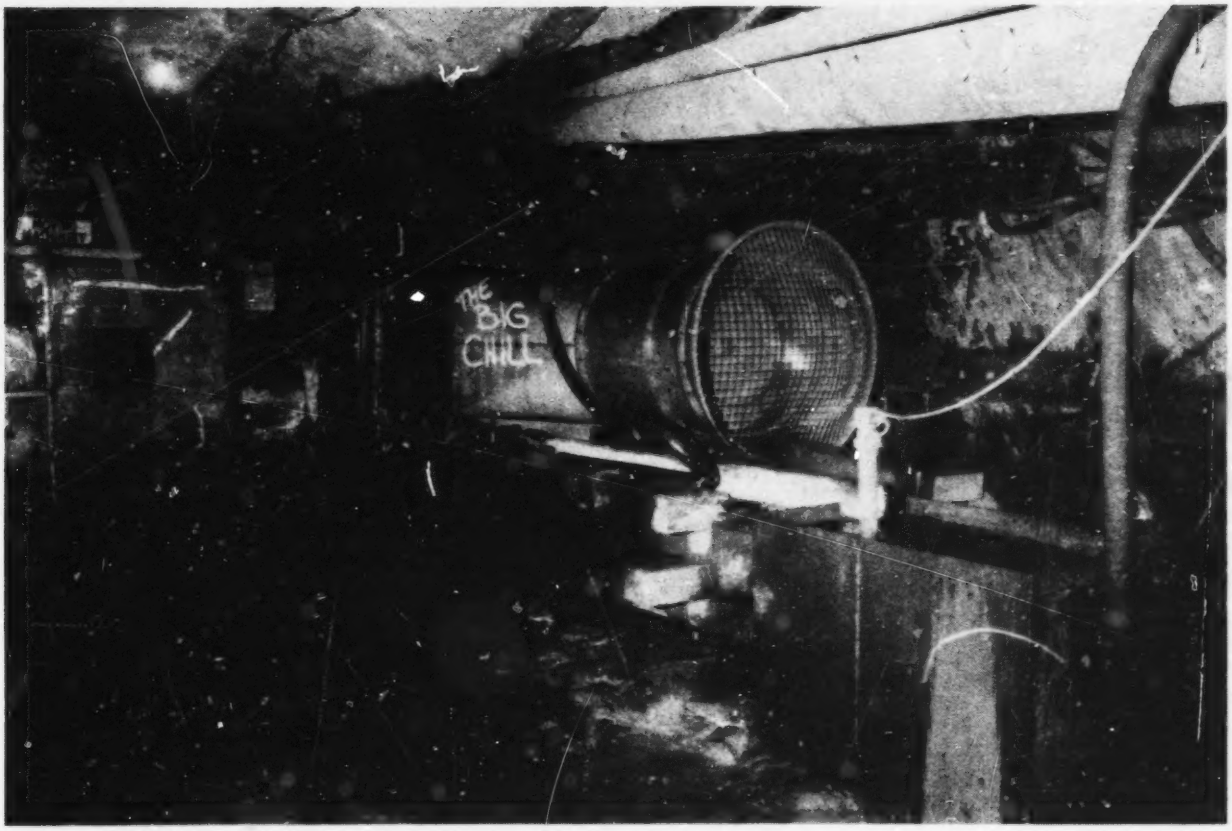

FIGURE 7. - Two-stage cooler installed in Homestake Gold Mine.

The three-stage cooler without an interstage mist eliminator is presently being installed 1,148 ft (350 m) downstream of the original chamber on the 7,100 level. It will service a VCR drawpoint area and a ramp system.

Maintenance on the first two coolers has been minimal. A few problems have resulted primarily from heavy blasting nearby and water quality. The mine service water has a total hardness of 2.29 $\times 10^{-3}$ lb/gal (275 mg/L), and the sprays naturally wash out some of the dust, emissions, and fumes from the air, to the benefit of crews downstream. However, these effects combine to clog second and third water stage nozzles, many of which can no longer be cleaned and are scheduled to be replaced. The intercooler piping also needs cleaning. The circulation pumps have required minor repairs, but have otherwise held up well. Scale deposited on the flow-straightening perforated plate in the two-stage cooler cut the airflow in half until the scale was removed with a chipping hammer. The mist eliminators have resisted scale buildup and have withstood heavy blasting very well.

However, heavy blasting has taken its toll on the 7,100 level (three-stage) cooler. Blasts consuming 10 st of powder have rocked the installation. Two windows were blown out, and the inlet transition guide vanes were knocked loose and subsequently removed in May 1984. Recent performance checks indicated that the F-factor has fallen significantly from its value at installation. The cooler will be fitted with a new inlet transition. This, along with a good cleaning and new nozzles, is expected to bring the F-factor up to at least 0.60.

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PERFORMANCE OF COOLERS

SINGLE-STAGE COOLER

The single-stage cooler, tested in the Mount Taylor Mine, achieved an average F-factor of 0.525 with a standard deviation of 0.015. This is considered good for a single-stage spray cooler with only horizontal airflow, and was achieved in spite of evidence of temperature stratification due to nonuniform air-water contact throughout the cooler. Nonuniform air-water contact could be expected due to the mine limit on cooler length, which prevented installation of an inlet transition to produce a flat velocity profile within the cooler. At the outlet of the mist eliminator, wet-bulb temperatures ranged from 7.6° to 12.4° F (4.2° to 6.9° C) higher near the corners than near the center. Elimination of this stratification would improve cooler performance.

TWO-STAGE COOLER

Installation and operation of the two-stage cooler at the Homestake Mine was somewhat different than called for by the original design. The outlet transition was removed since it was not necessary to duct outlet air. This reduced static pressure loss across the cooler. Significantly, the mine did not need 100 gal/min (6.31 kg/s) of chilled water for each cooler. For this cooler, approximately 55 gal/min (3.5 kg/s) of chilled water was supplied at 10 psi (69 kPa) to the first water stage. Water to the second water stage was pumped out of the sump at 72 gal/min (4.5 kg/s). This sump water was a mixture of water exhausted from the first water stage and recycled water that had been sprayed previously from the second stage. Excess water in the sump was drained into a tank at the inlet rate, 55 gal/min (3.5 kg/s). This water was subsequently pumped through a shell and tube condenser. The purpose of using recycled water in the second water stage was to promote a higher water-to-air loading for better heat absorption from the hot entering air.

Table 1 presents the two-stage cooler test results. The average F-factor was about 0.5. Temperature stratification of about 6.5° F (3.6° C) was observed in the outlet air and may explain the scatter of results. Since this cooler was not operated at the conditions or in the manner intended by the manufacturer, performance somewhat below the predicted F-factor of 0.6 was to be expected.

THREE-STAGE COOLERS

Although two three-stage coolers were built for testing at the Homestake Gold Mine, only the unit with two mist-eliminating sections was tested initially. At the time this report was written, the other three-stage cooler was being tested, but the test program had not been completed.

The cooler that was tested was modified for mine use. The outlet transition was removed, and, in this configuration, an air pressure loss of about 26,000 cfm (12.3 m^3/s) was measured at 1.8 in w.g. (450 Pa) with the water sprays on and 1.0 in w.g. (250 Pa) with the sprays off. The water supply to the stages was as follows:

First stage: chilled mine water; 50 gal/min (3.1 kg/s) at 30 psi (206 kPa).

Second stage: mixed first- and second-stage sump water; 82 gal/min (5.2 kg/s) at 35 psi (241 kPa).

Third stage: mixed second and third stage sump water; 87 gal/min (5.5 kg/s) at 40 psi (276 kPa).

Table 2 shows the results of the performance measurements. The average F-factor of 0.606 was very good. The data show that each of the three stages is important to achieving this level of performance.

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TABLE 1. - Two-stage cooler test results

Test	Stages tested	Water temp, °F		Air temp, °F			Water flow, gal/min	Air flow,[1] cfm	F-factor[2]	Cooling capacity, refrigeration tons
		In	Out	In		Out (saturated)				
				Wet bulb	Dry bulb					
1...	2	50	67.2	82.8	76.8	69.3	55	16,400	0.500	39
2...	2	50	66.9	82.4	76.6	69.5	55	17,000	.489	38
3...	1	50.1	65.5	81.8	76.9	70.9	55	18,000	.433	35
4...	2	51	67.9	83.6	77.7	69.5	55	14,600	.510	38

[1]Adjusted to obtain heat balance.
[2]Average F-factor was 0.500, excluding test 3.

TABLE 2. - Three-stage cooler test results

Test	Stages tested	Water temp, °F		Air temp, °F			Water flow, gal/min	Air flow,[1] cfm	F-factor[2]	Cooling capacity, refrigeration tons
		In	Out	In		Out (saturated)				
				Wet bulb	Dry bulb					
1...	3	49.6	70.9	85.3	76.7	69.8	50	20,200	0.571	44
2...	3	50.4	72.2	86.4	76.1	69.6	50	22,100	.612	45
3...	3	48.7	77.4	87.7	80.1	73.5	50	26,200	.645	59
4...	1,2	48.6	75.6	88.8	80.4	74.5	50	27,300	.572	56
5...	1	48.6	65.6	84.6	75.6	70.5	50	21,800	.436	35
6...	3	48.7	71.5	84.0	75.5	69.6	50	25,600	.596	47
7...	3	48.4	71.8	84.0	75.8	69.6	50	25,000	.606	49

[1]Adjusted to obtain heat balance.
[2]Average F-factor was 0.606.

DISCUSSION

The purpose of any ventilation system is to provide an intrinsically safe and physiologically tolerable underground work environment. Ventilation alternatives meeting these requirements are compared economically. Any characteristic of a given alternative can ultimately be reduced to an economic equivalent. Some factors influencing ventilation alternatives analysis are the mining method used, the contribution of various heat-load sources to the total heat load, surface ambient conditions, labor required to maintain production quotas, and the concentration of mining. Also important is the age of the mine, what services are available, and the condition of major airways.

Large spray coolers can be used in two ways. If used with duct as originally intended, their economics can be compared with spot coolers. If used in a limited-area bulk cooling capacity, some specific conditions must be met. Water at 53° F (12° C) or lower is absolutely essential. A water flow of 1.1 gal/min per refrigeration ton (0.02 kg/s per kilowatt of refrigeration), must be available to meet projected heat-load requirements. A number of headings can be serviced by a limited-area bulk cooler, but the areas must be in close proximity. If they are not, a larger number of smaller units may do a better job. However, work-area clusters should be scattered; if they are not, primary bulk cooling may be more economical.

A high factor-of-merit is not always essential for primary bulk cooling. The cooling duty may be met more effectively

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with a higher water flow rate and lower difference in temperature. With limited-area bulk cooling, however, a high factor-of-merit is essential. The water should remove as much heat from the air as practically possible when high pumping heads are involved, whether primary or limited-area bulk cooling is employed, even if energy recovery is employed on the intake water side. In this way, the quantity of intake water required is minimized, and pumping costs are reduced.

CONCLUSIONS

The three large-scale coolers tested all performed well under in-mine conditions. The 0.525 F-factor of the single-stage cooler and the 0.606 F-factor of the three-stage cooler can be considered very good. The two-stage cooler F-factor of 0.500 may appear to be on the low side, but it resulted from the unit being operated under conditions not considered in its design. All of the coolers tested have performed for significant periods of time with only minimal maintenance requirements.

Experience with these coolers demonstrated the difficulty of achieving high performance--an F-factor of 0.6 or greater--with only horizontal airflow. It took three stages of sprays with two electric pumps to reach this performance level with the three-stage cooler. In any spray cooler, good performance requires uniform distribution and thorough mixing of the air and water. This usually demands both a uniform air velocity profile and uniform water loading throughout the contact region. None of the large coolers achieved good, flat air velocity profiles. This indicates temperature stratification existed, resulting in loss of performance. Restrictions on cooler size is the major problem in trying to achieve flat air velocity profiles with minimal loss of air pressure. However, size restriction is an ever-present limitation for mining equipment, and solutions must be found within that constraint.

The use of the F-factor for characterizing cooler performance was invaluable in this research. This single number sums up the performance of a cooler, without regard for particular temperatures and flow rates. Laboratory testing requirements are dramatically reduced and can be quickly correlated to mine test results and vice versa. F-factors also facilitate comparisons between different coolers in different mines. As a unitless number, there is no confusion in international work where different conventions of units are employed; one number suits all.

Any cooling technique employed must be tailored to the individual application for which it is intended. The large spray coolers discussed in this paper may not be appropriate for all mines with heat problems, and, if they are employed, the manner in which they are used must be considered carefully in terms of the prevailing mining conditions.

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